Reconfigurable front-end antennas for cognitive radio applications

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Abstract: This study presents new antenna schemes suitable for cognitive radio communications. The antenna structures consist of a ultra wide band (UWB) sensing antenna, and a frequency reconfigurable communicating antenna both incorporated into the same substrate. Two different techniques to achieve the required frequency agility are proposed. The first one is based on a rotational motion of the radiating patch whereas the second is based on optical switching. The importance of these techniques is that no bias lines are needed as is seen in the case of RF MEMs, PIN diodes and lumped elements. Prototype antennas were fabricated and a good agreement was observed between the simulated and the measured data.

1 Introduction

In recent years, the growth of communication systems and the high demand for frequency bands have caused a perceived shortage in the available RF spectrum. This shortage is, however, mainly due to the inefficient spectrum allocation management policies rather than to the physical scarcity of usable frequencies [1–3]. In November 2002, the Federal Communications Commission (FCC) noted that the current overall spectrum is highly underutilised, where it is found that 70% of the allocated licensed spectrum remains unused [4]. The cognitive radios (CRs), built on a software defined radio platform, aimed to improve the spectral utilisation by dynamically interacting with the RF environment. These CRs are assumed to be intelligent communication systems that are able to learn from their environment and adapt to the variations of their surroundings. The adaptation process consists of updating the operational parameters such as the transmit power, carrier frequency, modulation strategy and transmission data rate in response to the observed RF environment [5, 6]. The two main objectives of CRs can be stated as: to ensure highly reliable communication whenever and wherever needed, and to efficiently utilise the radio spectrum.

Following its findings on underutilisation of the RF spectrum, the FCC suggested several broad solutions to improve the spectrum utilisation by proposing three different categories: spectrum reallocation, spectrum leasing and spectrum sharing, as shown in Fig. 1 [7].

Spectrum reallocation aims to provide a long-term solution and has resulted in the opening of the 700 MHz TV band for CR operation. Spectrum leasing, as was identified by FCC, presents an off-line solution according to which spectrum licensees are allowed to sell or trade their channels to third parties. On the other hand, the spectrum sharing solution has stimulated a great number of research activities aimed at dynamic sharing of the spectrum [1, 7, 8]. Many of the proposed dynamic spectrum sharing (DSS) approaches can be broadly classified as follows.

1.1 Open sharing

Here all users can simultaneously access the spectrum with some constraints on the transmit signal. These constraints are regulated by standard protocols. This approach is currently being used in unlicensed industrial, scientific and medical radio bands, in which IEEE 802.11 WiFi and Bluetooth, for example, coexist [9, 10].

1.2 Hierarchical sharing

In this model, the spectrum band is assumed to be owned by primary users who do not fully utilise their channels. These primary users may allow, or lease, their unused channels to unlicensed users, referred to as secondary users, as long as their quality of service is not compromised. In this category, three main paradigms have been considered so far, at least in current literature: spectrum underlay, interweaving and overlay.

In spectrum underlay, secondary users are allowed to transmit simultaneously with primary users as long as the transmission power is below a specific interference margin or a noise floor tolerated by primary users. An example is that of using UWB transmission, where secondary users can achieve a reasonable data rate with low power in short distance communication [11]. This approach is useful when primary users seem to transmit all the time. Underlay systems have been explored in many DSS proposals [7, 12, 13]. Many of them have suggested the use of game theory to allocate primary and secondary resources.

Unlike spectrum underlay in which the restriction on the secondary users is imposed on their transmit powers, a

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14. ABSTRACT

This study presents new antenna schemes suitable for cognitive radio communications. The antenna structures consist of a ultra wide band (UWB) sensing antenna, and a frequency reconfigurable communicating antenna both incorporated into the same substrate. Two different techniques to achieve the required frequency agility are proposed. The first one is based on a rotational motion of the radiating patch whereas the second is based on optical switching. The importance of these techniques is that no bias lines are needed as is seen in the case of RF MEMs, PIN diodes and lumped elements. Prototype antennas were fabricated and a good agreement was observed between the simulated and the measured data.

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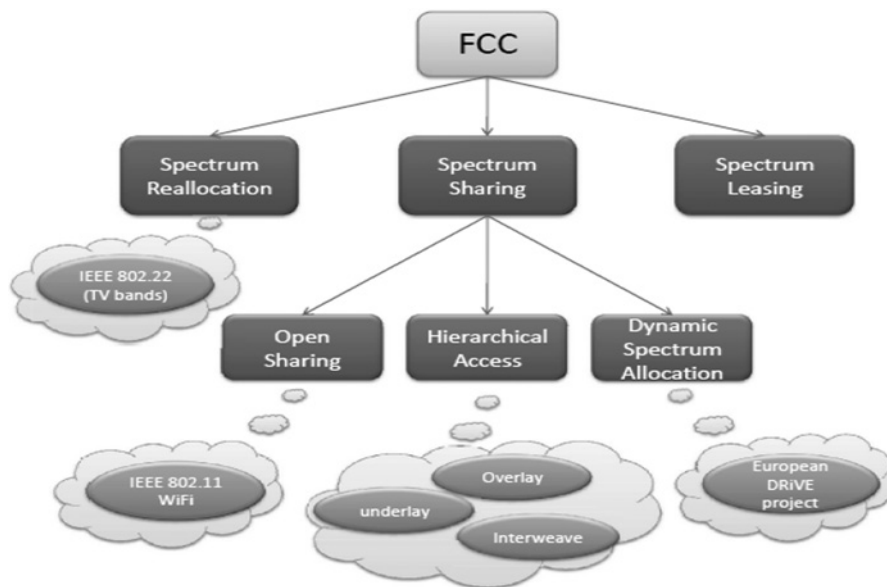**Standard Form 298 (Rev. 8-98)**
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Fig. 1 *Proposed FCC solutions to the spectrum underutilisation*

cognitive user, operating in spectrum interweave system, should determine where and when it may transmit. Secondary users try to locate the spectral holes, using an appropriate sensing mechanism. A spectrum hole is a licensed spectrum band that is owned by a primary system and is not utilised at a specific time and in a particular region. To be specific, the interweave permits secondary users to efficiently utilise the unused spectrum holes, while avoiding, or limiting, collisions with primary transmissions. This technique was envisioned by the DARPA Next Generation (XP) programme [14] and it was denoted as the opportunistic spectral access (OSA) [15, 16].

In spectrum overlay, cognitive users are assumed to know the primary message and they can use this knowledge in order to reduce the interference at the primary and secondary receivers, using sophisticated implementation techniques. For example, the overlay architecture can be implemented by using dirty paper coding which allows for the elimination of interference caused by the primary transmitter at the secondary receiver. On the other hand, spectrum overlay can be implemented in an asymmetric cooperative architecture in which the secondary transmitter spends a portion of its power to transmit its own signal, whereas the other portion is dedicated to relay the primary signal to its destination [11]. The advantage of the latter technique is that it allows secondary users to improve their signal-to-noise ratio without degrading the quality of the primary link. For instance, the authors in [17] adopt a game theoretic approach to determine the modulation rate of secondary users in spectrum overlay CR network. The main feature of spectrum overlay is that it allows cognitive users to improve their own transmission, simultaneously assisting primary communications through sophisticated techniques.

1.3 Dynamic spectrum allocation

This was considered in the European DRiVE project, in which the frequency bands are dynamically assigned to wireless services, depending on their spatial and temporal traffic statistics [1]. The dynamic assignment permits a wireless system to exclusively utilise the spectrum in a given region and for a specific time duration. However, this

approach does not completely eliminate temporal white spaces caused by the bursty traffic of wireless services.

In this work, we propose new techniques to design antenna systems for hierarchical sharing CRs on the basis of OSA. The basic RF architecture of such a system comprises of a 'sensing antenna' that continuously monitors the wireless channel and searches for unused frequency channels (spectrum holes) and a 'reconfigurable transmit/receive antenna' to perform the required communication within those unused frequency channels [18]. A top-level logic work-flow of one possible implementation of a CR communication scheme is shown in Fig. 2. The sensing antenna is generally a UWB antenna and would communicate with the 'spectrum sensing' module of the CR engine. The purpose of this module is to continuously search for unused frequency channels within the operating band of the sensing antenna. The information acquired by the 'spectrum sensing' module is fed to the 'spectrum decision' module, which determines the appropriate frequency band for communication. The 'switch controller' module then tunes the operating frequency of the reconfigurable antenna.
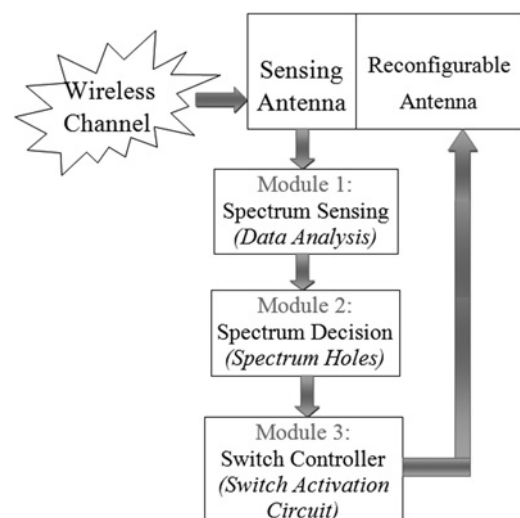

Fig. 2 *Generic CR work-flow diagram*

Recently various designs and architectures of a cognitive antenna have emerged. In [19], a co-located wideband and narrowband antenna is fabricated. The wideband antenna is a CPW fed printed hour-glass shaped monopole, which operates from 3 to 11 GHz. The narrowband antenna is a microstrip patch printed on the reverse side of the substrate, connected to the wideband antenna via a shorting pin and designed to operate from 5.15 to 5.35 GHz. A reconfigurable C-slot microstrip patch antenna is proposed in [20]. Reconfigurability is achieved by switching on and off two patches using PIN diodes. The antenna can operate in dual-band or in a very wideband mode. In [21], a quad-antenna with a directional radiation pattern is presented. The operating frequency can be adjusted using MEMS switches, making it suitable for CR applications. The authors in [22] incorporate the sensing and the reconfigurable antennas into the same substrate. The reconfigurable antenna is capable of operating between 2 and 10 GHz.

In this paper, two different techniques to achieve reconfigurable antenna designs of CR applications, are presented. Reconfigurability in the first technique is implemented via a rotational motion of the antenna patch, whereas in the second technique photoconductive pieces are considered as the switching elements. In both designs, the cognitive antenna structure incorporates a sensing antenna module and a reconfigurable antenna module into the same substrate. The sensing antenna covers the band from 3 till 11 GHz, whereas the reconfigurable antenna is able to tune its operating frequency through the band covered by the sensing antenna.

This paper is divided into the following sections. In Section 2, the two different reconfigurable structures are presented. In Section 3, we show the final cognitive antenna designs which are based on the two structures that are detailed in Section 2. Finally we conclude in Section 4 by summarising results presented in this work and by proposing future work.

2 Reconfigurable antenna designs

Reconfigurable multiband antennas are attractive in the case of many applications wherein it is desirable to have a single antenna that occupies the same real estate and if it can dynamically alter its transmit and/or receive characteristics to serve multiple frequency bands. The challenge lies in the methodology adopted to connect the radiating elements together, such that the resulting structure will yield the desired RF response over the frequency bands of interest [23, 24].

The most common methodology adopted in a reconfigurable antenna design is the inclusion of some form of switching circuitry. In the past, switches have been implemented using RF-MEMS [25], PIN diodes [26] or lumped elements [27]. MEMs switches possess good RF characteristics and can be used in low- and high-frequency
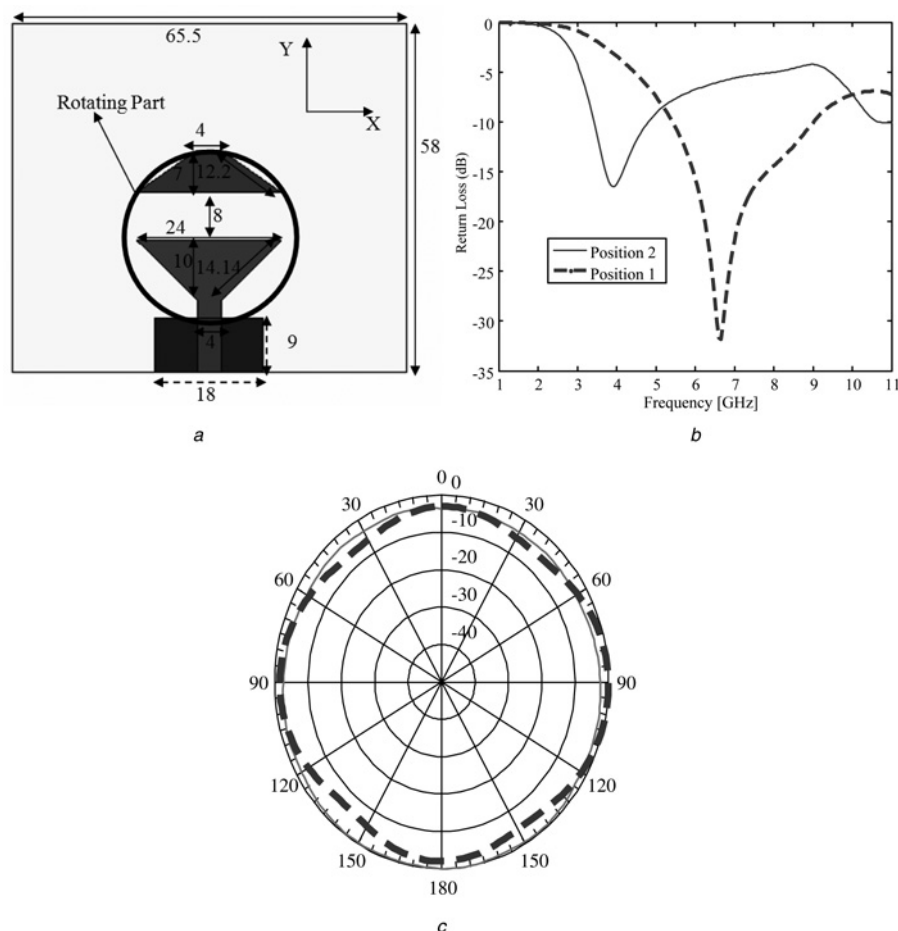

Fig. 3 *The first reconfigurable antenna design*

a Rotatable reconfigurable antenna structure
b Corresponding frequency tuning
c Normalised radiation pattern at both positions in the *XZ*-plane (solid line: 4 GHz, dotted line: 6.65 GHz)

applications [25]. A PIN diode is a versatile device and can be biased to behave like an open circuit, a short circuit or exhibit any desired reflection coefficient in between [28]. Despite all their advantages, the use of these switching elements requires the design of an appropriate biasing network for the activation/deactivation of the switch, which can affect the antenna performance and add further complexity to the antenna structure.

In this work, we propose new techniques to achieve frequency-reconfigurable antennas. The reconfigurability in the first design is obtained by feeding different antenna patches at different instances. This reconfiguration is achieved by a rotational motion. In the second design, silicon (Si) pieces are used as switching elements. Laser diodes are integrated within the antenna structure in order to deliver light to the photoconductive switches. In fact, rotational motion and photoconductive switches are proposed because of their superior performance in comparison to MEMs, PIN diodes and lumped elements. The rotational/photoconductive approach does not require the use of bias lines, which typically lie in the plane of the antenna and can interfere with the electromagnetic performance of the antenna. Also, photoconductive switches exhibit extremely fast switching speeds whereas the rotational motion of the antenna patch can be easily implemented via a stepper motor and which can be automated through a microcontroller/field programmable gate array (FPGA).

2.1 Rotatable reconfigurable antenna design

In this section, the structure of the rotatable reconfigurable antenna is detailed. A rotatable part of the antenna patch is responsible for production of the required frequency tuning. The corresponding antenna structure is summarised in Fig. 3a. By rotating the antenna patch by 180°, a different structure is being fed by the microstrip line. This rotation will produce different resonances, making the antenna suitable for communication at frequency bands specified by the 'sensing' antenna.

The antenna top layer consists of two triangular-shaped patches that are separated by a distance of 8 mm. This structure is fed via a microstrip line and has a partial ground of dimension 18 mm × 9 mm in the bottom layer. It is printed on a Rogers Duroid 5880 substrate with a dielectric constant of 2.2 and a height of 1.6 mm. This antenna is able to tune between $5.3-9.15$ GHz (position 1) and $3.4-4.85$ GHz (position 2), as shown in Fig. 3b. This is due to the fact that a different triangular shape is being fed at each position. Position 2 corresponds to the antenna structure shown in Fig. 3a. A voltage standing wave ratio (VSWR) that is less than 2 is taken as a limit for good operation of the antenna. The computed radiation pattern in the $X-Z$-plane at 6.65 GHz at position 1 (dotted line) and at 4 GHz at position 2 (solid line) is shown in Fig. 3c. At both positions, the antenna satisfies the omni-directional
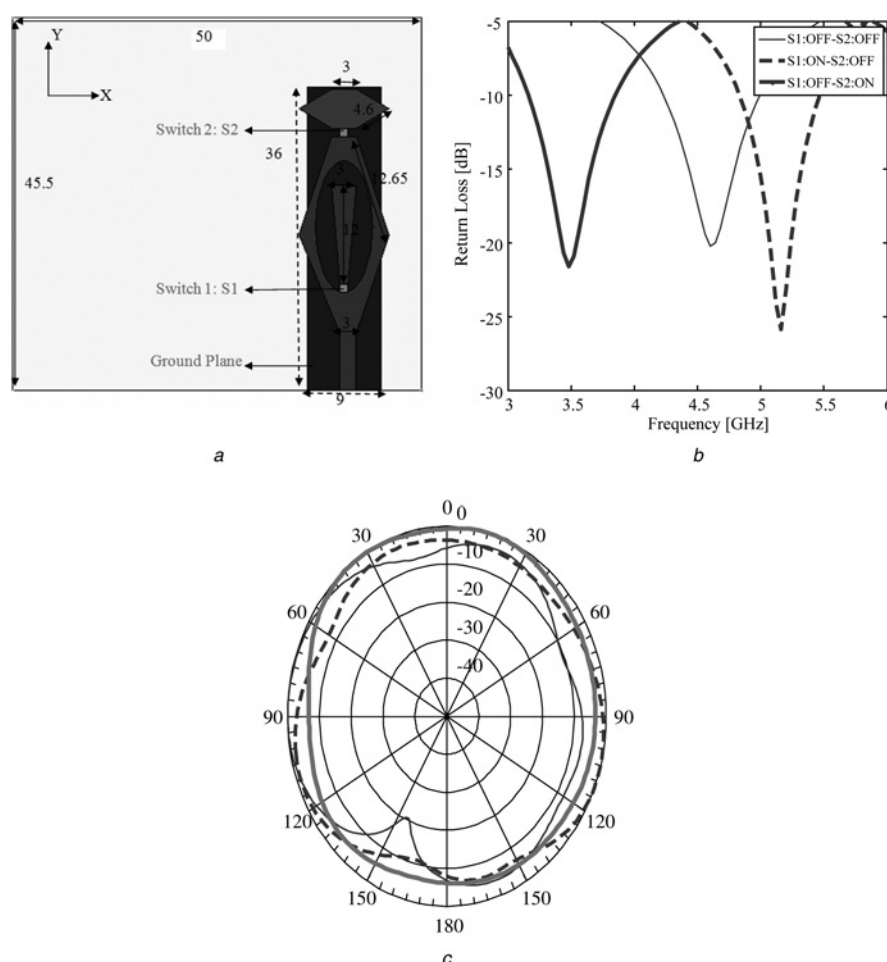

Fig. 4 *The second reconfigurable antenna design*

a Optically reconfigurable antenna structure
b Antenna return loss for different cases of the photoconductive switches
c Normalised radiation pattern in the $X-Z$-plane (thick line: 3.6 GHz, dotted line: 4.6 GHz, thin line: 5.2 GHz)

property. The substrate dimension is taken to be 65.5 mm × 58 mm, so as to accommodate the sensing antenna in the final CR design.

2.2 Optically reconfigurable antenna design

In this work, a 1 mm × 1 mm n-type silicon (Si) piece is the switching element. A laser diode is integrated within the antenna structure in order to deliver light to the switches. A

supply voltage of 1.9 V and a driving current of 87 mA are needed to make the laser diode generate an optical power of 50 mW. This power level is enough to make the silicon switch shift from the off state to the on state, and this is manifested by the increase in Si's total conductivity (DC + RF) [29–34].

The antenna is printed on a Taconic TLY substrate with a dielectric constant of 2.2 and a height of 1.6 mm. It is fed via a stripline and has a partial ground of the dimension
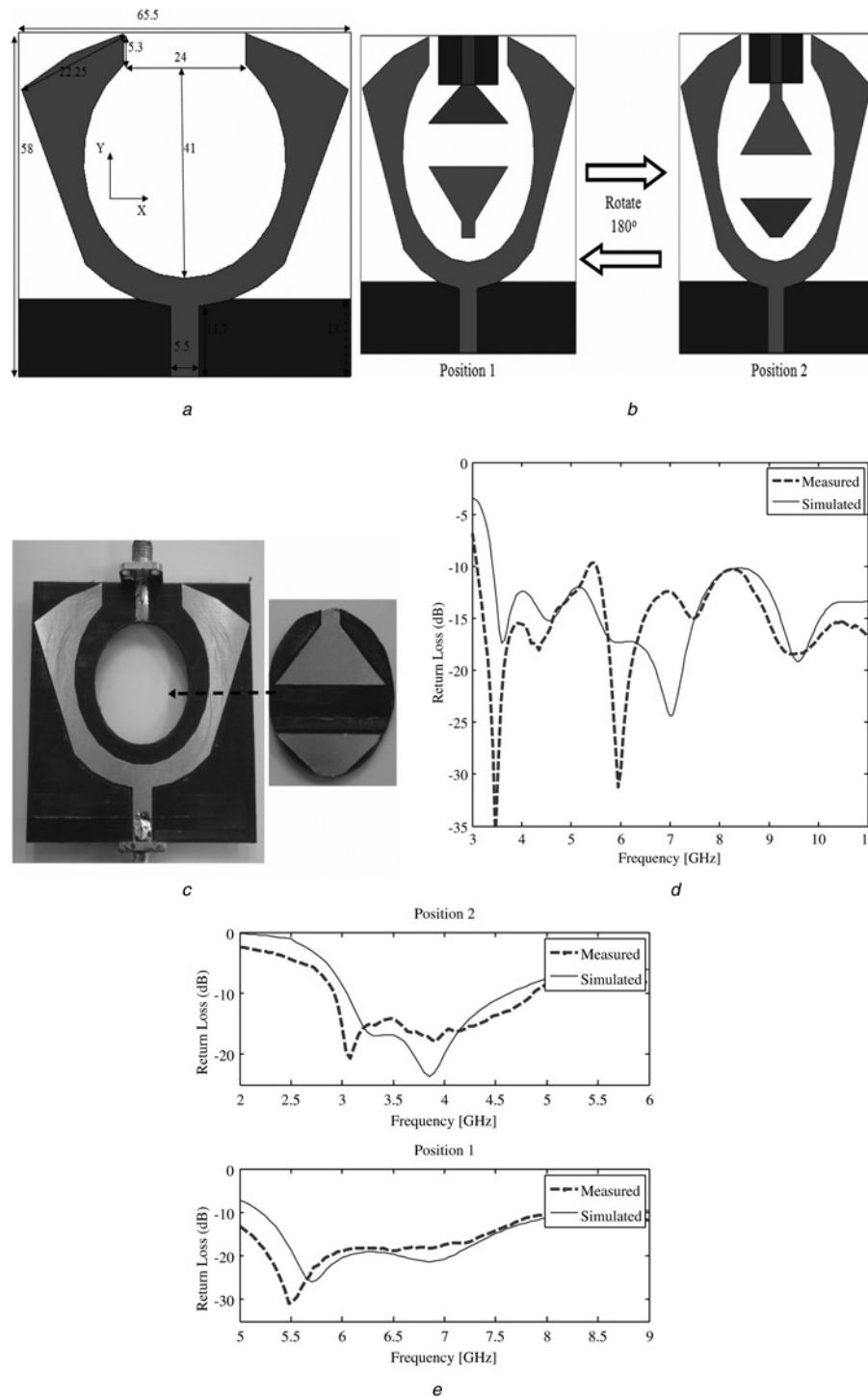

Fig. 5 *The complete rotatable reconfigurable cognitive radio antenna system*

a Sensing antenna structure
b CR antenna system
c Fabricated prototype
d Sensing antenna return loss for position 1
e Frequency tuning for the reconfigurable antenna

36 mm × 9 mm. Two silicon switches are included to connect the different radiating parts of the antenna's structure. Detailed dimensions of the different parts of the reconfigurable antenna are shown in Fig. 4a. Being similar to the first design, the antenna substrate is taken to be 50 mm × 45.5 mm so as to create space for the sensing antenna. The simulated antenna return loss in different cases of the optical switches is summarised in Fig. 4b. Frequency tuning is achieved from 3 to 6 GHz. Computed radiation patterns at $f = 3.6$ GHz (thick line, S1: OFF−S2: ON), $f = 4.6$ GHz (dotted, S1: OFF−S2: OFF) and at $f = 5.2$ GHz (thin line, S1: ON−S2: OFF) are shown in Fig. 4c. One can notice that a satisfactory omni-directional radiation pattern is obtained.

3 New antenna system for CR

In the previous section, we have discussed two different techniques to obtain reconfigurable antennas. In this

Table 1 Measured coupling (dB) for both positions

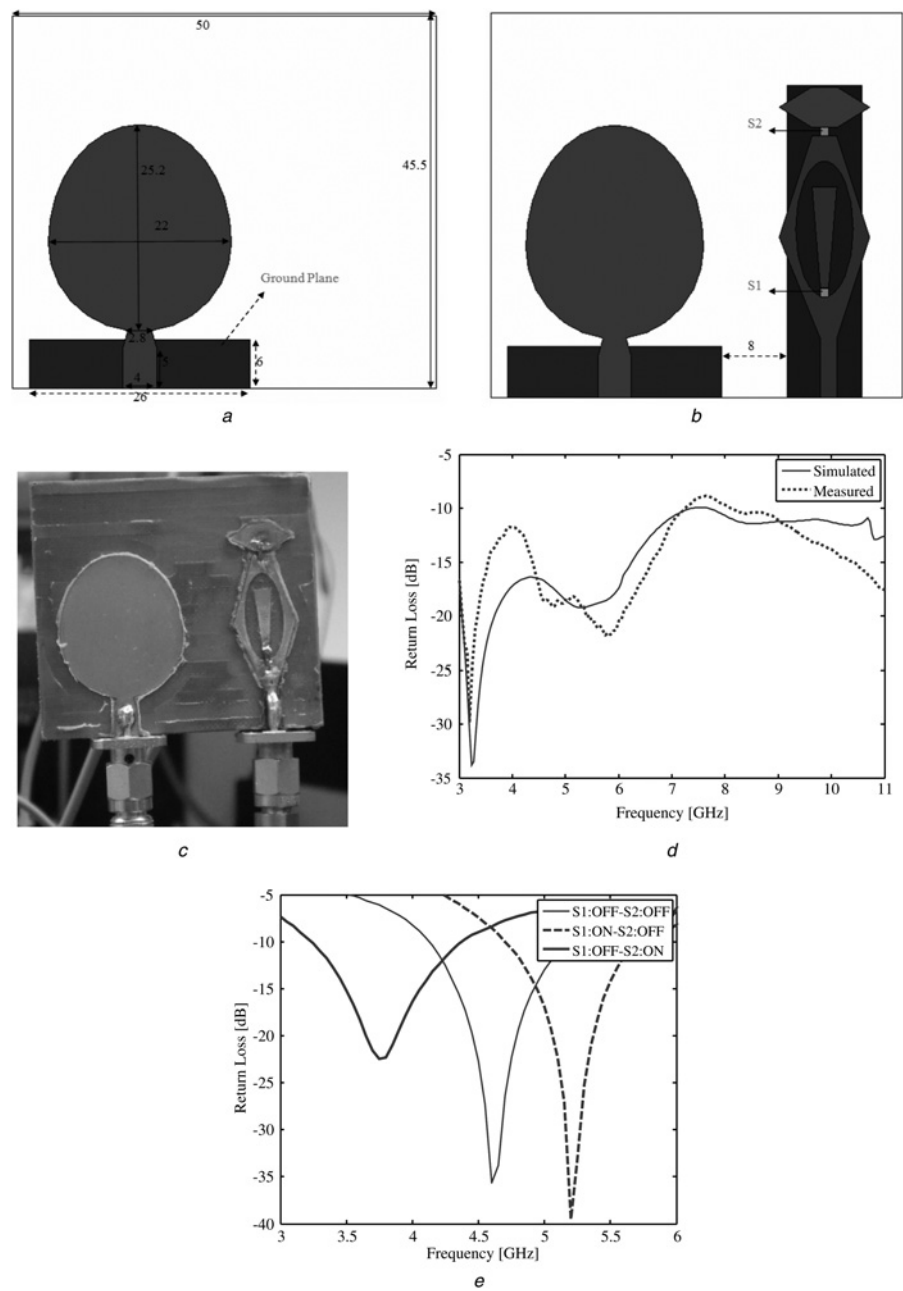| Frequency, GHz	Position 1	Position 2
4	−12.8	−18.2
6	−20.3	−18.14
8	−30.3	−24.26
10	−42.5	−41.1

Fig. 6 *The complete optically reconfigurable cognitive radio antenna system*

a Sensing antenna structure
b CR antenna structure
c Fabricated prototype
d Sensing antenna return loss when both switches are off
e Measured return loss for the reconfigurable antenna

section, we incorporate the previously presented reconfigurable antennas, with the sensing antenna, into the same antenna substrate. This has the advantage of reducing space requirements and making the two antennas required for CR communication lie in the same plane.

3.1 Cognitive antenna system based on rotatable reconfigurable antenna

The sensing antenna consists of a modified polygon-shaped patch. It has a circular slot since the rotatable reconfigurable section shall reside inside the slotted area. The dimensions of the sensing antenna structure are shown in Fig. 5a. The sensing antenna is able to cover the spectrum from 3 to 11 GHz. The suggested CR antenna structure is shown in shown in Fig. 5b in the case of both positions of the reconfigurable antenna. Dimensions of the reconfigurable antenna are the same as shown in the previous section. The fabricated prototype is shown in Fig. 5c. Comparison between the simulated and the measured return loss for the 'sensing' antenna is shown in Fig. 5d. This data corresponds to position 1. The same return loss is produced for the 'sensing' antenna if the entire antenna structure is at position 2. Fig. 5e shows the measured and the simulated return losses of the reconfigurable communicating antenna at both positions. The required frequency reconfigurability is achieved. The first plot corresponds to position 2 and covers the band from 3 to 5 GHz. The second plot corresponds to position 1 and covers the band from 5 to 9 GHz.

Since the sensing and the reconfigurable antennas are incorporated into the same substrate, it is imperative to examine the coupling between them. In fact, the amount of coupling is affected by the radius of the circular slot of the sensing antenna. The radius was optimised using high frequency structure simulator (HFSS) at both positions such that the coupling between the two antennas is below −10 dB throughout the entire band of interest. Table 1 shows the measured couplings of different sets of frequencies at both positions.

3.2 Cognitive antenna system based on optically reconfigurable antenna

The investigated structure consists also of a UWB antenna and an optically reconfigurable antenna, placed next to the other. The sensing antenna, shown in Fig. 6a, is a modified elliptical-shaped monopole. It covers the band from 3 to 11 GHz. A small tapered microstrip section matches the input impedance of the antenna to the input impedance of the patch. The design of the patch, the partial ground plane and the feed matching section guarantee the ultra wideband response of the sensing antenna. The corresponding CR antenna design is shown in Fig. 6b. Both structures (sensing and reconfigurable antennas) are fed via a stripline and have a partial ground in order to allow radiation above and below the substrate. The reconfigurable antenna possesses the same dimensions as these discussed in the previous section. The fabricated prototype is shown in Fig. 6c.

A comparison between the measured and the simulated return losses of the sensing antenna is shown in Fig. 6d. The antenna is able to cover the spectrum from 3 up to 11 GHz. A good agreement between both data is obtained. These data correspond to the case wherein both switches are off. The same return loss is obtained in other cases of switches. As for the reconfigurable antenna, when the two silicon switches (S1 and S2) are not illuminated by a laser

Table 2 Measured coupling (dB) for the three different states of the swithches

Frequency, GHz	Both off	S1: ON	S2: ON
4	−25.7	−23.5	−24.61
6	−27.12	−23.2	−25.49
8	−26.65	−25.06	−37.85
10	−36.25	−26.8	−30.5

light (off state), the antenna operates between 4.15 and 5.1 GHz. Upon activation of the first switch (S1), achieved by driving the laser diode via a current of 87 mA and a voltage of 1.9 V (this correspond to 50 mW output optical power), the antenna shifts its resonance to the 4.8−5.7 GHz band. By illuminating the second switch (S2), using the same amount of pumped power, the band 3.2−4.3 GHz is covered. The measured return loss is summarised in Fig. 6e. A good agreement is obtained between the simulated and the measured return loss of the reconfigurable antenna and this can be observed by comparing Figs. 4c and 6e.

Since both structures are incorporated into the same antenna substrate, it is essential to examine the coupling between the sensing and the reconfigurable antennas. The distance between the two structures was optimised to achieve the minimum coupling with regard to the entire band from 3 up to 11 GHz. The measured coupling of a set of frequency for the three different states of the switches is shown in Table 2.

4 Conclusion

In this paper, we propose two different techniques to achieve a frequency reconfigurable antenna for CR systems. In the case of both designs, no bias lines are needed to activate the switches. This allows for an easier integration of the antenna in a complete RF chain and reduces the amount of complexity that is introduced by the use of bias lines. A stepper motor is needed to achieve the required rotation with the rotatable reconfigurable CR antenna. Laser diodes should be incorporated with an optically reconfigurable antenna design. The amount of output optical power can be adjusted via a laser current driver and can be controlled via a computer or a microcontroller. In the case of both designs, a prototype antenna was fabricated to prove the proposed method. A good agreement was achieved between simulation and measurements. The two proposed antennas are a good candidate for future CR communication systems. As for future work, we will try to control rotation of the reconfigurable communicating antenna via an FPGA or a microcontroller. Also, we will investigate techniques to reduce the transition thresholds of the photoconductive switching elements.

5 Acknowledgments

6 References

1 Zhao, Q., Sadler, B.M.: 'A survey of dynamic spectrum access', *IEEE Signal Process. Mag.*, 2007, **24**, (3), pp. 79–89
2 FCC: 'Report of the spectrum efficiency working group'. FCC spectrum policy task force'. Technical Report, November 2002

3 FCC: 'ET docket no 03-322 notice of proposed rulemaking and order'. Technical Report, December 2003

4 Yau, K.-L., Komisarczuk, P., Teal, P.: 'A context-aware and intelligent dynamic channel selection scheme for cognitive radio networks'. Fourth Int. Conf. Cognitive Radio Oriented Wireless Networks and Communications 2009, Hannover, Germany, June 2009, pp. 1–6

5 Mitola, J.: 'Cognitive radio: an integrated agent architecture for software defined radio'. PhD dissertation, Royal Institute of Technology (KTH), Stockholm, Sweden, 2000

6 Haykin, S.: 'Cognitive radio: brain-empowered wireless communications', *IEEE J. Sel. Areas Commun.*, 2005, **23**, (2), pp. 201–220

7 Jayaweera, S., Mosquera, C.: 'A dynamic spectrum leasing (DSL) framework for spectrum sharing in cognitive radio networks'. Record Asilomar Conf. Signals, Systems and Computers, 2009, Pacific Grove, CA, USA, November 2009, pp. 1819–1823

8 Molisch, A., Greenstein, L., Shafi, M.: 'Propagation issues for cognitive radio', *Proc. IEEE*, 2009, **97**, (5), pp. 787–804

9 Lehr, W., Crowcroft, J.: 'Managing shared access to a spectrum commons'. First IEEE Int. Symp. New Frontiers in Dynamic Spectrum Access Networks (DySPAN'05), Baltimore, MD, USA, November 2005, pp. 420–444

10 Etkin, R., Parekh, A., Tse, D.: 'Spectrum sharing for unlicensed bands', *IEEE J. Sel. Areas Commun.*, 2007, **25**, (3), pp. 517–528

11 Goldsmith, A., Jafar, S., Maric, I., Srinivasa, S.: 'Breaking spectrum gridlock with cognitive radios: an information theoretic perspective', *Proc. IEEE*, 2009, **97**, (5), pp. 894–914

12 Jayaweera, S.K., Vazquez-Vilar, G., Mosquera, C.: 'Dynamic spectrum leasing: a new paradigm for spectrum sharing in cognitive radio networks', *IEEE Trans. Veh. Technol.*, 2010, **59**, (5), pp. 2328–2339

13 Lin, Y.-E., Liu, K.-H., Hsieh, H.-Y.: 'Design of power control protocols for spectrum sharing in cognitive radio networks: a game-theoretic perspective'. IEEE Int. Conf. Communications (ICC'10), Cape Town, South Africa, 23–27 May 2010, pp. 1–6

14 The Next Generation (XG) Program. Available at http://www.darpa.mil/sto/smallunitops/xg.html

15 Xiao, Q., Gao, Q., Xiao, L., Zhou, S., Wang, J.: 'An optimal opportunistic spectrum access approach'. IEEE Int. Conf. Communications Workshops, 2009, Dresden, Germany, 14–18 June 2009, pp. 1–5

16 Hoang, A.T., Liang, Y.-C., Wong, D., Zeng, Y., Zhang, R.: 'Opportunistic spectrum access for energy-constrained cognitive radios', *IEEE Trans. Wirel. Commun.*, 2009, **8**, (3), pp. 1206–1211

17 Pillutla, L., Krishnamurthy, V.: 'Game theoretic rate adaptation for spectrum-overlay cognitive radio networks'. IEEE Global Telecommunications Conf. (GLOBECOM'08), New Orleans, LO, USA, November 2008, pp. 1–5

18 Christodoulou, C.G.: 'Cognitive radio: the new frontier for antenna design', *IEEE Antennas Propag. Soc. Feature Artic.*, 2009 available at www.ieeeaps.org

19 Ebrahimi, E., Hall, P.S.: 'A dual port wide-narrowband antenna for cognitive radio'. The Third European Conf. Antennas and Propagation, March 2009, pp. 809–812

20 AbuTarboush, H.F., Khan, S., Nilavalan, R., Al-Raweshidy, H.S., Budimir, D.: 'Reconfigurable wideband patch antenna for cognitive radio'. 2009 Loughborough Antennas and Propagation Conf., November 2009, pp. 141–144

21 Wu, G.T., Li, R.L., Eom, S.Y., *et al.*: 'Switchable quad-band antennas for cognitive radio base station applications', *IEEE Trans. Antennas Propag.*, 2010, **58**, (5), pp. 1466–1476

22 Tawk, Y., Costantine, J., Christodoulou, C.G.: 'Implementation of a cognitive radio front-end using rotatable controlled reconfigurable antennas', *IEEE Trans. Antennas Propag.*, 2011, **59**, (5), pp. 1773–1778

23 Tawk, Y., Christodoulou, C.G.: 'A cellular automata reconfigurable microstrip antenna design'. IEEE Antennas and Propagation Society Int. Symp., June 2009, pp. 1–4

24 Tawk, Y., Costantine, J., Christodoulou, C.G.: 'A frequency reconfigurable rotatable microstrip antenna design'. IEEE Antennas and Propagation Society Int. Symp., July 2010, pp. 1–4

25 Anagnostou, D.E., Zheng, G., Chryssomallis, M.T., *et al.*: 'Design, fabrication, and measurement of an RFMEMS-based self-similar reconfigurable antenna', *IEEE Trans. Antennas Propag.*, 2006, **54**, (2), pp. 422–432

26 Lai, M.I., Wu, T.Y., Hsieh, J.C., Wang, C.H., Jeng, S.K.: 'Design of reconfigurable antennas based on an L-shaped slot and PIN diodes for compact wireless devices', *IET Microw. Antennas Propag.*, 2009, **3**, pp. 47–54

27 Behdad, N., Sarabandi, K.: 'Dual-band reconfigurable antenna with a very wide tunability range', *IEEE Trans. Antennas Propag.*, 2006, **54**, (2), pp. 409–416

28 Mak, A.C.K., Rowell, C.R., Murch, R.D., Mak, C.L.: 'Reconfigurable multiband antenna designs for wireless communication devices', *IEEE Trans. Antennas Propag.*, 2007, **55**, (7), pp. 1919–1928

29 Sze, S.M.: 'Physics of semiconductor devices' (John Wiley & Sons, 1981, 1st edn.), pp. 704–748

30 Saleh, E.A., Teich, M.C.: 'Fundamentals of photonics' (John Wiley & Sons, 2007), pp. 42–94

31 Balanis, C.A.: 'Advanced engineering electromagnetic' (John Wiley & Sons, 1989, 2nd edn.), pp. 627–677

32 Tawk, Y., Albrecht, A.R., Hemmady, S., Balakrishnan, G., Christodoulou, C.G.: 'Optically pumped frequency reconfigurable antenna design', *IEEE Antennas Wirel. Propag. Lett.*, 2010, **9**, pp. 280–283

33 Tawk, Y., El-Husseini, M., Albrecht, A.R., Hemmady, S., Balakrishnan, G., Christodoulou, C.G.: 'Implementation of a cognitive radio front-end using optically reconfigurable antennas'. Int. Conf. on Electromagnetic in Advanced Applications, September 2010, pp. 294–297

34 Tawk, Y., Albrecht, A.R., Hemmady, S., Balakrishnan, G., Christodoulou, C.G.: 'Optically, pumped reconfigurable antenna system (OPRAS)'. IEEE antennas and propagation society Int. Symp., July 2010, pp. 1–4